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MATERIALS AND PROPERTIES OF COMPONENTS FORMED USING THE 3DWIRE PROCESS

CONF-980716--

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ABSTRACT

Direct metal deposition technologies produce complex, near net shape components from CAD solid models. Most of these techniques fabricate a component by melting powder in a laser weld pool, rastering this weld bead to form a layer, and additively constructing subsequent layers. Powder feed material in these processes results in near net shape, high strength components, with the ability to blend materials for novel properties. This talk will describe a new direct metal deposition process, known as 3DWire, whereby a small diameter wire is used instead of powder as the feed material to fabricate components. This allows for faster deposition rates, smoother surface finishes, and easy material handling. Currently, parts are being fabricated from 308L stainless steel and Aermet® 100. Microscopy studies show the 3DWire parts to be fully dense with fine microstructural features. Initial mechanical tests show stainless steel parts to have good strength values (σ_y= 58 ksi, σ_{ult}= 95 ksi, 87 HRB) with retained ductility (65%).

INTRODUCTION

Laser processing has the potential for revolutionizing the rapid prototyping field to impact rapid manufacturing of metallic components. Various groups are coupling high power lasers with metal powders to layer additively fabricate metallic components [1-4]. Typically, a laser beam is focused onto a substrate to create a weld pool into which powder particles are simultaneously injected to build up each layer. The substrate is moved beneath the laser beam to deposit a thin cross section, or the desired geometry. Subsequent layers are additively fabricated, thereby building a three dimensional (3D) component.

Metallic powders work well for the described direct metal deposition technologies, but create other problems. A key aspect is material or powder utilization. Typical systems require a high velocity spray of powder to insure even material build up; however, only a small amount of the powder is actually retained in the weld pool, approximately 20%. With wire feedstock, 100% utilization is achieved during

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* This work supported by the U. S. Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

fabrication, where all wire injected into the weld pool is used to fabricate the part. Therefore no recycling system is required and faster build times can be accommodated. Furthermore, even flow of the powder material is crucial to the success of fabrication in laser/powder technologies, where control can be difficult to maintain and sensors to measure fabrication build height with closed loop control are a necessity to reliably build parts. It is relatively simple to maintain even wire feed rates and this should lead to simpler sensors and control schemes for unattended operation.

Another consideration is availability of material; most materials are readily available in wire form. Direct metal deposition with powder feedstock requires a good powder source, where size distribution and composition must be carefully controlled. This paper will describe the 3DWire process, the resultant material properties for as-processed 308L stainless steel, and preliminary modeling results of the process.

3DWIRE PROCESS

Figure 1 shows a schematic of the 3DWire process. The system consists of a CW 600W Nd:YAG laser, a 4-axis computer controlled positioning system, and a wire feed unit [5]. The positioning system and wire feed unit are mounted inside a box with localized gas purge capability. During fabrication, the work piece and surrounding area are purged with argon to minimize oxidation of the workpiece. The laser beam is brought into the box through a window mounted on the top of the box and directed to the deposition region using a six inch focal length plano-convex lens. The wire feed system is designed to inject the wire into the weld pool from one side, and the lens and wire feed system move as an integral unit.

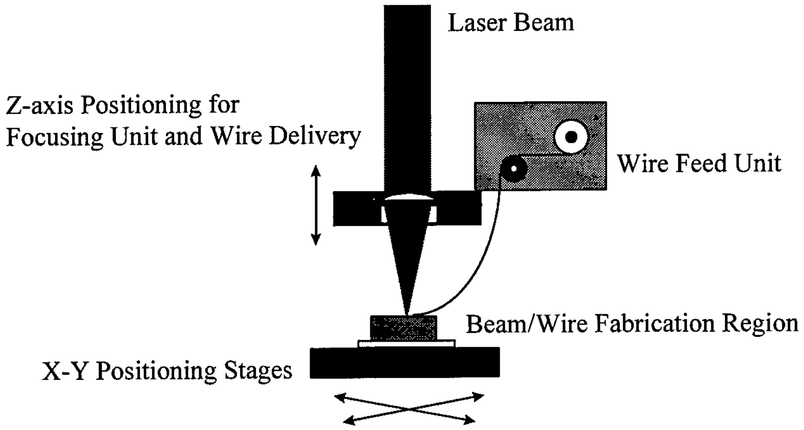


Figure 1. Schematic of the 3DWire system.

Simple geometries are written into a series of tool path patterns to build each layer. This file is combined with other commands to drive the laser, the positioning stages, and the wire feed unit to produce the desired component one layer at a time, starting from the bottom of the part. A solid substrate is used as a base for building the 3DWire object. The laser beam is focused onto the substrate to create a weld pool in which fine wire, typically 0.010" diameter, is injected into the molten pool to build up each layer. The substrate is moved beneath the laser beam to deposit a thin cross section, thereby creating the desired geometry for each layer. After deposition of each layer, the wire feed mechanism and focusing lens assembly are incremented in the positive Z-direction, building a three dimensional component layer additively.

RESULTS

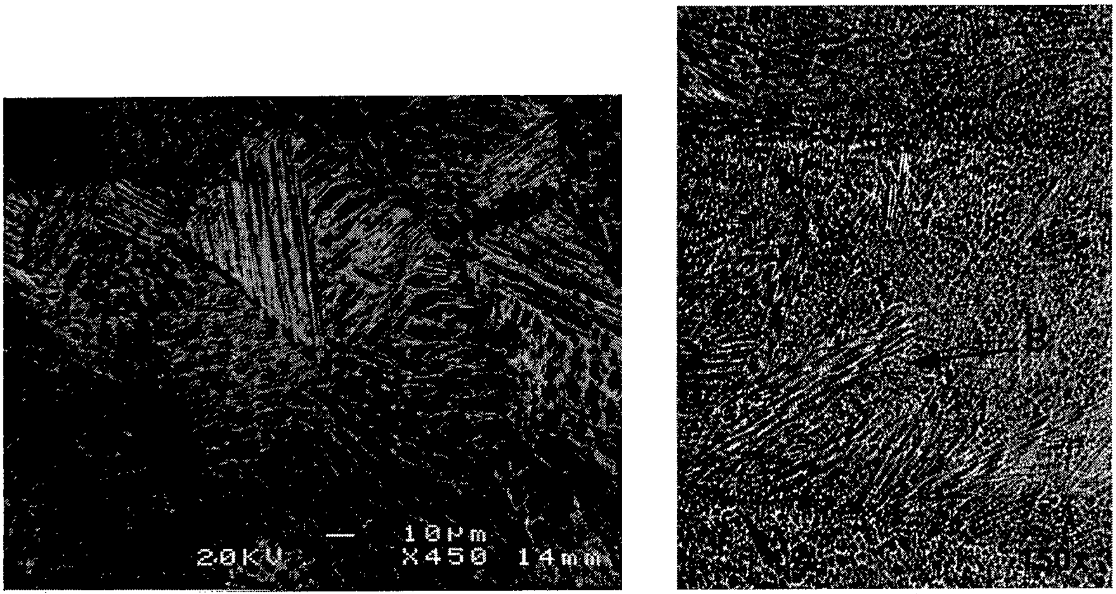
(1) Shape Fabrication

Initially, test matrices were developed and implemented to identify the key factors controlling the 3DWire process. The key processing variables include: laser power, wire feed rate, wire feed direction and angle, and traverse velocity. From previous work with LENS [6], laser power, wire feed rate, and traverse velocity are the key factors to control deposition in direct metal fabrication. Along with those tests, extra experimental studies were required to understand the relationship between the wire and the weld pool. This study included varying the wire feed direction, wire feed height (w.r.t. the substrate), and insertion angle. Diagnostic tools, such as high magnification video camera techniques, were used to monitor and understand the wire/weld pool interaction. The wire must intersect the weld pool in such a manner to maintain stability along the solidification front. If the wire is inserted too high (w.r.t. the substrate), it does not remain connected with the pool; if the wire is inserted too low, the wire either stubs on the substrate or is pushed around by the force of the weld pool. After choosing the intersection point, the angle insertion and direction must be determined. An insertion angle of 45 degrees maintains the best stability, and even deposition is only maintained with wire insertion perpendicular to the major weld direction. The consistency of build is not maintained if the wire is inserted either from the trailing or leading edge of the weld pool, because the weld pool has difficulty forming and maintaining the bead as the source material or energy moves away.

From the process variable experiments, the laser wire deposition parameters were optimized to demonstrate feasibility of part fabrication. New test matrices were added to understand how layer thickness and hatch (fill) spacing affected part fabrication. Process studies to control the wire feed during layer increments for simple block shapes were a major activity. After a layer is fabricated in a serpentine draw pattern, the laser shutter closes, and the focusing lens and wire feed units must increment in the positive Z direction to fabricate the next layer. This is required for subsequent layer deposition and, eventually, for complex part fabrication with increasing area complexity. After a layer is fabricated, the wire must reliably 'burn off' or detach from the part before the Z increment. With this understanding, we were able to increase the geometric complexity of 3DWire fabrication. We have fabricated three types of geometries: 1) uni-directional fabrication using a rotary stage to build hollow cylinders, 2) bi-directional patterns to fabricate walls, and 3) with an understanding of wire detachment, hatch spacing and layer thickness, it was possible to fabricate dense, rectangular shapes from 308L stainless steel. All shapes possess 100% utilization of the wire, where the material inserted into the weld pool is directly used to produce a block. 3DWire parts were quickly fabricated, at approximately 1 hour per cubic inch.

(2) Material Characterization

Metallographic analysis reveals dense, fine grain microstructures for 308L stainless steel produced by the 3DWire process as shown in Figures 2 (a) and (b). Figure 2(a) is a cross-sectional view of a line drawn by the 3DWire process. Typical microstructural features are on the order of 4 microns, due to the high solidification rate in the 3DWire process. Figure 2(b) is a top view showing one full line and two partial lines (interfaces between lines marked at A). The fine microstructural features show directional solidfication behavior with textured features (example point marked at B).



(a) (b)

Figure 2(a) and (b). Typical microstructures for 308L stainless steel, where (a) is a view inside a fabrication line (450x) and (b) is a view of three lines fabricated in a layer (150x).

Coupons were machined from the as-processed 308L stainless steel for room temperature tensile testing, where the pull direction is parallel to the build plane in the 3DWire system. All samples had densities greater than 98%. The results for 3DWire-processed material is compared to typical wrought material] in Table 1. With grain size refinement, the 3DWire material possesses strengths greater than wrought, where the yield strength is 58 ksi as compared to 35 ksi for the wrought material. However, the ductility rermains consistent with values of 65-75%, which are slightly higher than the wrought values (55-65%). High strengths and hardness with retained ductility is a good combination for 3DWire-processed material properties.

Property	3DWire	Wrought material
Hardness	$87R_B$	$80R_B$
Microstructure feature size	4 Micron	40 Micron
Tensile strength (Yield)	58.2 ksi	35 ksi
Tensile strength (Ultimate)	94.2 ksi	85 ksi
Ductility (Elongation)	64.9%	55%
Ductility (Reduction in area)	74.6%	65%

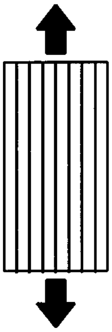
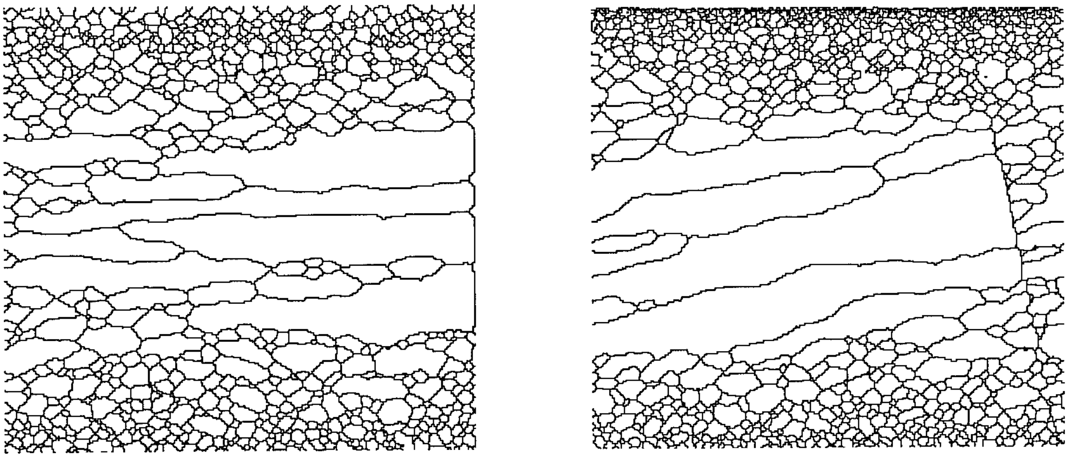


Table 1. Room temperature mechanical properties for as-processed 308L stainless steel compared to typical wrought material. Tensile pull direction is parallel to layer fabrication as shown in the schematic.

(3) Predictive Modeling

The Potts Monte Carlo model was modified to simulate microstructural evolution during the 3DWire process [7]. Two major components were added to the model, the addition of material in the 2D plane of a layer (e.g. wire) and the evolution of the microstructure in a dynamic temperature profile. The resulting simulation was capable of predicting the elongation of the grain structure as a function of the temperature profile and raster speed of the laser. It was also able to show that misalignment of the laser beam with the raster direction leading to asymmetry in the elongated grain structures. Figures 3(a) and (b) show these results. These results are over-exaggerated in grain structure and growth, but reveal the trends as shown in Figure 2(b). Real-time temperature data will correlate the model with the experimental results.



(a) **(b)**

Figure 3(a) and (b). Microstructures resulting from Potts model simulations of 2D coarsening in the rastering temperature field of the 3DWire process when the laser beam is (a) aligned and (b) tilted with respect to the raster direction.

Current research is to extend this model into 3D. A 3D model will allow us to simulate the effect of the Z-direction of the temperature profile under the laser beam on microstructural evolution. Once the model is developed, it will be used to simulate microstructural evolution to aid in process development of the 3DWire process.

CONCLUSIONS

With the 3DWire process, high fabrication rates (one hour per cubic inch) can be achieved with 100% utilization of feed material. As-processed stainless steel parts have strengths, greater than traditional wrought material, but with retained ductility. Preliminary modeling of the 3DWire process shows the correllation between the laser beam profile and raster speed with the resulting microstructure. The 3DWire system is simple in design, requiring only a localized gas purge to removed unwanted oxidation during fabrication. This allows for easy part removal and change of wire material. Future work will develop complex geometry fabrication, where the theoretical model will be able to predict the resulting microstructure for a given material and process conditions.

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M98001698

Report Number (14) SAND--97-3116C
CONF-980716--

Publ. Date (11) 199712
Sponsor Code (18) DOE/CR, XF
UC Category (19) UC-904, DOE/ER

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